IN THE UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF VIRGINIA
Norfolk Division

R.M.S. TITANIC, INC.,
successor-in-interest to
Titanic Ventures, limited partnership,
Plaintiff,

v. **Civil Action No. 2:93cv902**

THE WRECKED AND ABANDONED VESSEL,
ITS ENGINES, TACKLE, APPAREL,
APPURTENANCES, CARGO, ETC., LOCATED
WITHIN ONE (1) NAUTICAL MILE OF A POINT
LOCATED AT 41 43' 32'' NORTH LATITUDE
AND 49 56' 49" WEST LONGITUDE,
BELIEVED TO BE THE R.M.S. TITANIC
in rem,
Defendant.

DECLARATION OF DAVID L. CONLIN

I, David L. Conlin, pursuant to 28 U.S.C. § 1746, declare under penalty of perjury that the following statement is true and correct.

1. I am the Chief for the United States National Park Service's Submerged Resources Center, and have been so employed since January 2010. In that capacity, I oversee a team of archeologists, underwater photographers and support specialists who provide scientific expertise for underwater archaeology and underwater operations to the National Park Service and other partners both nationally and internationally. We are operationally involved in underwater operations and fieldwork approximately seven months of the year. I hold a Ph.D. and a M.A. in anthropology from Brown University; a B.A. in anthropology from Reed College, and a M.St. from Oxford University in maritime and Aegean archaeology. I have been actively engaged in the field of underwater archaeology for 33 years and have served as an underwater archaeologist for the National Park Service from 1996 to present. I have been Chief of the National Park Service Submerged Resources Center since 2009, and was the Acting Regional Archaeologist from 2017 to 2018. A copy of my resume is attached.

2. I have been asked by NOAA to review and provide my input on the sufficiency and adequacy of the "RMS *Titanic* Expedition 2020 Research Design" ("Research Design") In addition to the Research Design, I have also reviewed a memorandum provided by RMST to the Court with the Research Design; prior materials submitted by RMST to the Court preliminarily outlining RMST's plan; NOAA's response to these earlier submissions; and, the transcript from a hearing held on February 20, 2020. I am not

being compensated for my review beyond my salary with the National Park Service (which has approved my consulting on this matter). My statements are derived from my training, education and experience and do not necessarily reflect any official position or expression of the National Park Service.

3. In my role as an Underwater Archaeologist for the National Park Service I was part of the science team for the 2010 investigations of RMS *Titanic*. My other team members included Dr. James Delgado, William Lange, David Gallo, David Alberg, and Evan Kovacs. Over the course of several years we worked together both in person and remotely to plan, execute, and interpret the results of the 2010 expedition to *Titanic*. As a part of the team my responsibilities included:
    1) Helping to develop a non-intrusive scientific research design that would provide information about the impact of the deep marine environment on *Titanic*, as well as the impact of *Titanic* on the marine environment.
    2) Helping to create and organize the Geographic Information System (GIS) database for *Titanic*. This is a collection of electronic maps that can be superimposed on each other and interrogated to provide information about the wrecksite and its components.
    3) Providing expertise and input for a scholarly article discussing the rationale and results of our scientific tests and their results.
    and
    4) Participating in discussions and scoping sessions to frame hypotheses and tests that could provide credible, science-based information on the current condition and long-term stability of the remains of *Titanic*.

4. My position with the 2010 *Titanic* science team came largely from my scientific work on the battleship USS *Arizona* that was bombed and sunk by the Japanese in Pearl Harbor Hawaii in 1941. Since 2000, the National Park Service has been engaged in a complex, interdisciplinary scientific study of the remains of USS *Arizona* involving experts from multiple disciplines. Our main research focus is assessing the current and likely future rates of corrosion and degradation of the ship. This is because it is the final resting place for almost one thousand sailors and marines and because the ship still contains an estimated 500,000 gallons of Bunker-C fuel oil. The National Park Service is balancing the potential environmental impacts of leaking fuel with the need to preserve an memorial to the service and sacrifice of our military.
    1) I began work on the *Arizona* project in 2000 and have been the Project Director for scientific research on the ship from 2008 to present.
    2) USS *Arizona*, although a battleship and not a passenger liner, is contemporaneous with RMS *Titanic*. *Arizona* was launched in 1915, *Titanic* in 1911. The ships share similarities in construction materials and methods. My work with the 2010 *Titanic* expedition included adapting scientific analyses and explanations derived from *Arizona* to *Titanic*.
    3) USS *Arizona*, although actively corroding on the outside, displays a high degree of preservation and minimal corrosion in the interior spaces. During our studies we have measured very low oxygen in the water of the Second Deck compartments leading to low interior corrosion rates. This low oxygen

environment has preserved uniforms still on hangers in closets, uniform hats, blankets and even paper in books despite 75 years of immersion in shallow, warm water.

4) Scientific principles and approaches taken from fields such as physics, chemistry, metallurgy, engineering, computer science, microbiology and biology that have application on USS *Arizona* also have applicability to the study and understanding of RMS *Titanic*.
5) Over the past twenty years, the scientific studies of USS *Arizona* and the application of similar approaches to other shipwrecks have been published in dozens of articles in peer reviewed journals and symposia worldwide.
6) A key product from our work on USS *Arizona* was modelling the structural stresses and likely curve of decay for the ship utilizing engineering principles and computer models. A copy of one of our scientific reports about this is attached. An approach like this, applied to *Titanic*, would be one way of forecasting structural changes and deterioration in the years to come.
7) Like USS *Arizona*, RMS *Titanic* is a gravesite of international importance with profound lessons related to humanity, sacrifice, and loss that continue to resonate and teach new generations. Because of their dramatic poignancy, both of these ships occupy a preeminent place in world maritime history.

5. In addition to studying the corrosion and preservation of *Arizona* and *Titanic*, I have been involved in numerous projects throughout my career that included the study of metal objects in seawater. Applicable examples to my declaration include the study and recovery of the Confederate submarine *H.L. Hunley* that was lost during an attack on the Union blockade ship USS *Housatonic* off Charleston South Carolina on February 17, 1864; and the examination of a 6th century AD Byzantine merchant ship off the Greek island of Kythera.
    1) The National Park Service recommended that *Hunley* be recovered due to the shallow depth of the wreck and the likelihood of looting and vandalism to the ship.
    2) When recovered, the submarine displayed a very high degree of preservation and structural integrity with extensive preservation of organic remains in the interior of the vessel.
    3) In 1997, during project work around the island of Kythera for the Hellenic Institute of Marine Archaeology in Greece, we examined the remains of a 6th Century AD Byzantine merchant ship in about 130 feet of water. Despite being approximately 1500 years old and in a relatively shallow location, we noted two intact iron anchors as part of the ship’s fittings.

6. Our research on *Arizona* and other shipwrecks have shown that far from being a uniform process of corrosion and collapse that accelerates over time, the decay of an iron structure underwater generally proceeds in fits and starts, progressing quickly shortly after sinking and then more slowly over time.
    1) Ships are complex structures made up from hundreds of thousands or even millions of component parts. Each of these parts interacts with others in complex ways that affect their preservation and degradation.

2) Different metal components interact electrochemically in similarly complex ways with some metals corroding preferentially to others in the way that sacrificial zinc anodes attached to an outboard motor corrode to preserve the aluminum and steel of an outboard motor. Corrosion of one element of an iron wreck may therefore contribute to the preservation of another element nearby.
3) Even small differences in the metallic makeup of a ship's fittings can make it more susceptible to corrosion than an adjacent fitting; the same fitting in a different area of a shipwreck may be well preserved due to a different microenvironment. On USS *Arizona*, for example, we see very low levels of dissolved oxygen in the interior compartments, leading to overall better preservation and lower levels of corrosion. Therefore, based on scientific studies we have done on *Arizona* and other underwater sites we can say that corrosion and decay is not uniformly distributed over a shipwreck.
4) Shipwrecks typically decay in a series of "punctuated equilibria" whereby a rapid change is followed by a period of slower or even imperceptible change that may last for years, decades, or centuries. If external conditions are altered, the nature of this equilibrium may change, and decay may increase or decrease depending on how the conditions are altered.
5) As shipwrecks decay over time, as a general rule, the most fragile elements decay and collapse first, leaving the stronger and more robust elements in place. Thus, the rate at which a ship decays and collapses slows over time.
6) As a physical structure, when one section of a shipwreck collapses, the load carried by that section, as well as the weight of materials from that section propagates to other areas of the ship. Those other areas may likewise fail or the collapse may change the local microenvironment of corrosion and decay leading to better or worse preservation and long term stability.

7. My comments will focus primarily on RMST's proposed recovery of the Marconi Wireless Telegraph and related equipment artifacts from within the *Titanic*'s hull, and specifically, within the "Marconi Suite." Based on my review of the Research Design, RMST expects to access the artifacts from the deck above the Marconi Suite through either an existing skylight opening, or if that is not feasible, by cutting another opening in the deck to access the artifacts below. I will comment briefly on other aspects of the project research design, but will not comment on aspects of the proposed work beyond that. A lack of comment on some aspect of the proposed work should not be taken as my tacit agreement with the proposed work.

8. RMST asserts that *Titanic* is corroding and collapsing at such a rate that if they do not recover materials now, they will be lost forever (Exhibit A- Project Plan pp16-17). Exhibit A-Project Plan page 64 states "In the next few years, the overhead for the Silent Room is expected to collapse, potentially burying forever the remains of the world's most famous radio." Nowhere in this document or in the quoted literature is this assertion supported by scientific data or peer reviewed publication. Furthermore, several of the quotes supporting this assertion are incomplete, given undue weight, are subjective, or do not address the totality of the long-term structural decay of *Titanic*. Specifically:

1) Page 16: NOAA's statement of a 50 year lifespan for the vessel (made 19 years ago) is a synopsis of impressions, not based on scientific information. Were this statement true, one would expect to see approximately 40% decay and loss of the ship in 2019. Clearly this is not the case.
2) Page 16: McCarty and Foecke's statement describes the process of decay and structural collapse, but does not address the likely rate at which this will occur.
3) Page 16: Dr. Foecke's comment in Murray 2012, appears offhand for a popular science article and is not supported by data or analysis. Dr. Foecke himself would likely have a much more nuanced answer to that question if it was posed by the Court and could, at a minimum, specify the broad outlines of data needed to scientifically support or refute the immanence of decay and collapse asserted by RMST.
4) Page 16: Peter Rubinstein is a science writer for the BBC, not a marine microbiologist or marine engineer and therefore is not in a position to extrapolate with any degree of credibility scientific findings related to the effects of marine microbes on the ship. Additionally, his references lead to other popular and sensationalized accounts of the decay of *Titanic* from other writers for the BBC or other general news organizations like the Daily Mail.
5) Page 16: Lori Johnston does not assert an increased rate of decay, but merely comments on the impact to the ship if, in fact, this is the case.
6) Page 16: Ed Coughlan's quote is merely his opinion of the validity of the opinions of others—it is not, apparently, based on his evaluation of any scientific data, nor would he necessarily be in a professional position to evaluate those data if they existed and were presented to him.
7) Page 16: Henrietta Mann offered up what appears to be an opinion calling for a 15 or 20 year lifespan. We have no basis for understanding why she said that nor any supporting evidence or documentation in the quoted materials. As with the NOAA statement above, this is now 9 years old, so we would expect to see massive and significant deterioration in the current structure of *Titanic*, which we do not.
8) Page 16: My quote, "The wreck has been degrading gradually over the past 100 years. There is no evidence to support a dramatic change in the environmental conditions which would change this," is not given in full. The complete quote is actually: "The wreck has been degrading gradually over the past 100 years. There is no evidence to support a dramatic change in the environmental conditions which would change this. The wreck is a very complex structure made up of many different materials and is sure to be around for many years to come."
9) Page 17: Robert Bylth's comment is merely an expressed opinion that the wreck should be "used while it has something to say." That opinion does not address the rate of decay or collapse of the site, nor does it clarify how *Titanic* might be able to "speak." If the implication is that the site can only speak through the recovery of artifacts, it ignores may other possible ways to share the stories from the ship.
10) Page 17: P.H. Nargeolet and David Gallo's court testimony is backed by first hand experience and a wealth of time on the site and working with the materials, but still constitute subjective impressions and anecdotal instances that may or may

not be generalizable to the entirety of the site itself. Again, we do not have scientific evidence in this document to back up the assertions presented.

11) Page 18: Daley's comments about decay and change, while perhaps true in specific instances, may or may not pertain to the entire ship. His statement that the "…mass of metal is quickly deteriorating due to rust, salt. Colonies of sea creatures and the constant flow of the ocean currents," is not supported by any data and is thus an assertion.
12) Notably too, testimony from the RMST expert underwater archaeologist, Dr. John Broadwater (590-1, Exhibit 1 p. 5) offers up his own opinion based on the opinions of others, not on a scientific evaluation or collection of data germane to the questions of decay and structural stability.
13) While Dr. Broadwater clearly lays out some of the important questions for the court to evaluate prior to granting permission for the recovery of elements of the Marconi wireless (590-1, Exhibit 1, p. 6) he offers no answers to the questions he has posed. While there may be several reasons for this, two likely ones are that either: a) He was not provided the necessary data to form defensible answers to these questions; or b) The data necessary to answer these questions do not currently exist.
14) In summary, the supplied documents do not provide sufficient data to support RMST's assertion that the ship is undergoing rapid, imminent decay and collapse, and therefore their assertion that portions of the Marconi Apparatus should be recovered do not follow as a justified response. RMST's own expert, Dr. John Broadwater, (590-1, Exhibit 1, p. 5) states: "<u>The draft recovery plan is not sufficiently developed to permit me to make a detailed assessment</u>; however, the plan specifies personnel and equipment that I believe are well suited to the proposed recovery" (Emphasis mine).

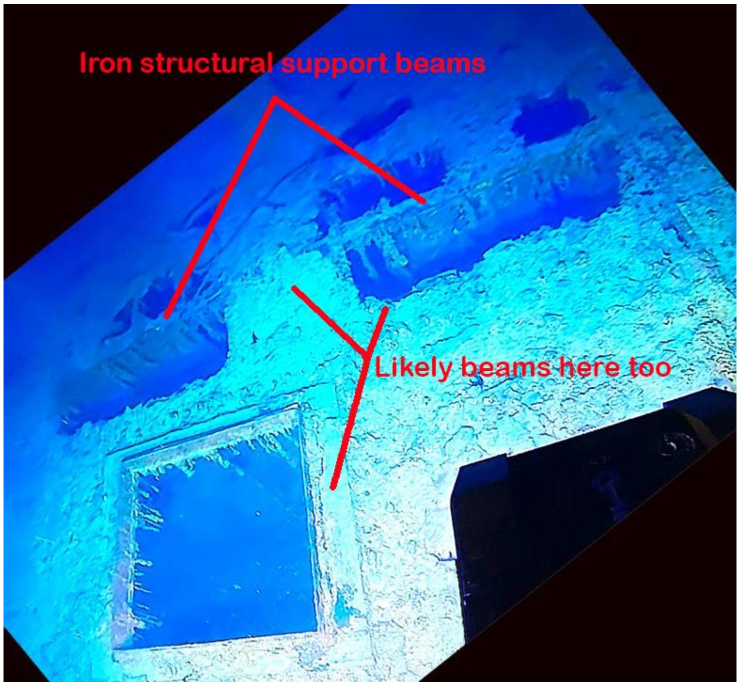
9. RMST is not proposing to recover the entirety of the Marconi wireless apparatus, only select portions of it (Exhibit A- Project Plan p.24, 46, 49, 50). They propose to recover wall mounted switchboards and regulators as a primary goal (p.46), and the spiral inductance, tuning lamp and earth arrester, and low frequency inductor (p.48-50) as a secondary goal. If possible, they will recover the motor generator set with disk discharger as a secondary goal as well (p.48).
    1) These actions are permanent and irreversible, likewise any collateral damage done to the Marconi Suite or its other artifacts or structure to facilitate the recovery of materials is also permanent and irreversible. Because these actions are permanent and irreversible, future research and exploration of these spaces will be impaired.
    2) The proposal makes no mention of, nor does it discuss the possibility of, the recovery of all elements of the Marconi wireless.
    3) Currently the entirety of the Marconi radio apparatus sits complete as it was when the ship sank, in the location of its use as the final voice for *Titanic*. As such it evinces "the power of place" where its power as a touchstone to history is drawn as much from *where* it is as it does from *what* it is. It is currently surrounded by the structure of *Titanic* and, almost certainly, by the mortal remains of more than 1500 people who died during the sinking. Just like a lion is much better

appreciated in the wilds of the African savannahs than it is stuffed in a museum, so too does the Marconi apparatus best tell its story and share its value where it is.

4) RMST's statement of a "Surgical Removal" of pieces of the apparatus notwithstanding (585-1, Exhibit 1, p.4), recovery of portions of the Marconi device effectively dismember it and cheapen the value of both the recovered elements and those that are left behind.
5) RMST (Exhibit A p.26) states that they will tell the *Titanic* story through the recovery and display of artifacts. However, telling the story of the Marconi wireless and the heroism of *Titanic*'s radio operators is not contingent on the dismemberment and partial recovery of the device they used. For USS *Arizona*, we have had significant impactful results from non-destructive video footage from the interior spaces in video productions like the one linked here: https://vimeo.com/250871636 and here: https://vimeo.com/240696163. In short, the Research Design has not clearly established the educational and scientific benefits that would outweigh or at least mitigate negative impacts to the integrity of *Titanic* caused by recovery operations.
6) As a side note, the caption for the Low Frequency Inductor on page 9 of Exhibit 2 (585-2): "Also acts as an articulation frame for the warp drive dilithium crystals," is a *non sequitur* reference to the science fiction TV series Star Trek that may be funny elsewhere but is an inappropriate affront to the seriousness of what we are discussing here.

10. RMST is not clear on how they will access the Silent Room of the Marconi Suite to recover portions of the Marconi Wireless, or how much collateral damage will result. Absent better delineation of equipment such as the submarine, ROV, manipulators etc. that they propose to use, as well as integrating this equipment into the known or possible environmental variables such as current and interior visibility we have no basis to know, nor even speculate as to how much damage might occur.
    1) Exhibit 2, p. 3 (585-2) "An overhead skylight orginally [sic] ventilated the sleeping quarters and operator's office, tinted green in the drawing below. This has now become the preferred point of entrance into this part of the wreck."
    2) Exhibit A, p. 54 "If the Marconi Room cannot be adequately accessed via the skylight, then the senior expedition team must decide if if [sic] it is feasible to recover artifacts from the Marconi Room without excessive physical impact to the hull."
    3) Exhibit A, p. 23 "RMST is simply proposing to remove small sections of the badly corroded ¼ inch (6.35mm) thick deck that is also the ceiling of the Marconi Suite, and only if necessary to gain access to components of the Marconi apparatus located below these already weakened areas."
    4) From the evolution of what is proposed documented above, it may be the case that the decision to remove portions of the deck has already been made. If so, we have no idea of how much of the deck will be removed nor, as a consequence, the impact on the remaining structure of the Marconi Suite and its contents subsequent to the recovery.
    5) The deck is supported by beams under it. These beams are the structural component to the Marconi Suite in the deck house near the Deck Officer's

Quarters and the First-Class Cabins (585-2, Exhibit 2, p.1). The photograph of the skylight and ceiling over the Marconi Suite below is taken from Exhibit A, p. 45 and annotated to indicate what I infer as iron beams that supported the ¼ inch iron ceiling:



6) No information is provided by RMST in this plan about the spacing or location of the deck support beams relative to the areas of decking that may be removed, therefore we do not know if beams will have to be cut and if so what the impact on the remaining structure will be. Absent any particulars, we can say with certainty that cutting roof support beams would diminish the overall integrity of the structure that surrounds the Marconi Suite. This would almost certainly lead to more rapid decay and collapse.
7) We have no idea what will happen to the areas of decking (and or beams) that are removed- will they fall into the Marconi suite, will the material be discarded, if it retains structural integrity will it be replaced? Will something be left to cover any holes that are cut?
8) The removal of decking (and/or beams) over the Marconi Suite and opening up that space may have an impact on long-term interior water chemistry or water flow inside the shipwreck. Introduction of more oxygenated water to interior spaces of a shipwreck will result in more rapid degradation of metals and artifacts as a general rule. Conversely, less oxygenated water will typically show a lower degradation and deterioration of materials and artifacts, as we saw with the *Arizona*. I would expect that less exposed, lower oxygen levels within the *Titanic* would be more preserved.
9) The plan proposes to use a small suction dredge to remove sediment and silt from the silent room in advance of artifact removal (Exhibit A, p.25, 53, 54). A suction dredge uses water flow to suck up loose sediment that covers archeological materials like an underwater vacuum cleaner. Sediment and silt cover typically preserve organic and inorganic remains—materials that are uncovered and not

recovered for conservation would be expected to decay more rapidly after their uncovering. In addition, small artifacts that are not easily seen by the ROV may be damaged or lost when sucked into the dredge.

10) I have no doubt that recovery operations will be done by some of the best, if not the best ROV pilots and remote manipulator operators in the world, however I still question the ability of any robotic manipulator to recover small, delicate materials without damage to them or other objects that surround them.

11) Due to the paucity of descriptive plans and a general lack of knowledge about the environmental conditions in and around the Marconi Suite, we have no idea what the necessary, likely, and possible long-term impacts of recovery operations to the remaining structure and the artifacts it likely contain will be.

11. In addition to elements of the Marconi Wireless, RMST also proposes to evaluate other artifacts from the Marconi Room for recovery (Exhibit A, p.51) These include the pneumatic wall clock; the spark coil and adjuster; two brass spheres that set the spark gap; hollow brass cylinders used to send received messages to the Enquiry Room by brass vacuum tubes; a telegraph "key" used to send messages in Morse Code; and a framed wall chart showing the Marconi designation codes for major ships at sea.
    1) As discussed above, due to the paucity of recovery plans and details, we have no idea what the necessary, likely, and possible long-term impacts of recovery operations to the remaining structure and the artifacts it likely contains will be.

12. RMST is not providing a clear evaluation of the necessary, likely, or possible long-term damage to *Titanic* that will result from their plans, nor are they providing any evaluative criteria for determining what will lead them to the decision to proceed or cease in their efforts to recover elements of the Marconi apparatus from the interior of the ship.
    1) Terms such as "minimally invasive" (Exhibit A, p. 24, 25, 53, and 54) and "minimal adverse effects" (Exhibit A, p. 24) are too subjective to evaluate in advance of the proposed efforts; "Surgical Removal" (Exhibit 1, p.4) is not an apt term for the robotic cutting and removal of iron deckplates.
    2) There is no transparency in what will drive the decision making process of the team, nor a list of who will be on the decision making team, nor is there an established hierarchy of authority or accountability in the project team structure as presented.
    3) As a practical point, based on my decades of experience working on archaeological projects with large and small teams and large and small budgets, I am extremely skeptical that RMST will mount a multimillion dollar expedition to *Titanic* with an expressed aim of recovering elements of the Marconi Apparatus and then decide not to proceed unless they reach a point where the financial risks involved in the recovery of the apparatus (e.g. potential loss of the ROV) significantly approach the costs of mounting the expedition itself.

13. Other elements of the RMST research design, although incompletely described, have scientific and educational merit and pose no or little danger to the integrity and continued preservation of *Titanic*.

1) Video documentation of the exterior and interior (where feasible) of *Titanic* will help understand the current conditions of the wreck, provide visually stimulating and educational imagery for both scientists and the general public. These missions could be easily modified to include scientific payloads or sensors that would provide objective data germane to assessing the processes of preservation or decay at work on *Titanic*.
2) Selective recovery of artifacts from the debris field for conservation and inclusion in the larger collection poses no threat to the structure of *Titanic*.
3) Inclusion of more complete criteria for deciding what artifacts to recover or leave in place would make it easier to understand and support the proposed actions.

14. Conclusions.

1) RMST asserts, but provides no scientific evidence of, the rapid deterioration and imminent collapse of the structure surrounding the Marconi Suite.
2) RMST's sources for the support of this assertion are weak, incompletely quoted, offer no scientific evidence, are subjective, or offer irrelevant opinions in the place of facts.
3) RMST is using this assertion of immanent collapse to justify intrusive and possibly damaging interventions to recover elements of the Marconi Apparatus.
4) RMST has not clearly delineated the degree of intervention and subsequent impact to the structure of the ship necessary to reach the apparatus, nor the point at which that intervention exceeds an acceptable level and would cease.
5) RMST has not delineated clearly the decision making process, the team involved or the evaluative criteria used to decide whether or not to proceed with the recovery of parts of the Marconi Apparatus.
6) RMST is not proposing to recover the entirety of the apparatus, only selective elements of it.
7) The dismemberment of a sophisticated machine with the subsequent removal from its context of use and meaning will cheapen the scientific and educational value of both the recovered elements and those that are left behind.
8) While the remains of *Titanic* may be difficult to access now, advances in marine robotics, telepresence and other ways to experience the site, may make it possible and easier at some point in the future. By invasively intervening into *Titanic* now RMST will degrade the quality of the resource and rob those who will come in future years of the opportunity to experience the site as it lays, largely undisturbed, on the floor of the Atlantic Ocean.
9) Other actions in the proposed Research Design, although incompletely described, have scientific and educational merit and pose no or almost no threat to the continued preservation of *Titanic* as a complex structure and touchstone for one of the most important events in world maritime history.

4-27-20
Date

David L. Conlin, Ph.D.

David Lawrence Conlin

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Submerged Resources Center
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Education:

Brown University, Providence, Rhode Island

Ph.D. Anthropology (May 1999). Specialization in anthropological approaches to the ancient Greek world, anthropological approaches to underwater archaeology.

Dissertation: "The World Wind Made: The Nautical Geography of the Mycenaean World" Advisor Dr. Richard Gould.

Comprehensive Examinations: Passed December 1994; European prehistory, Underwater archaeology, Archaeological method and theory.

A.M. Anthropology May 1994

Thesis: "The Loggerhead Reef Ship Trap: Site Formation Processes on DRTO-036 and Beyond." Advisor Dr. Richard Gould.

Coursework includes: Ship design, construction and use, the archaeology of Europe, the Mediterranean, and the Middle East, underwater archaeology, ethnoarchaeology, historical archaeology, hunters and gatherers, civilizational complexity, North American archaeology, socio-cultural theory, anthropological linguistics, sociolinguistics, philosophy of science, modern Greek literature and language.

American School of Classical Studies in Athens, Athens Greece

AIA Olivia James Travelling Fellow 1996-1997

Ph.D. Dissertation research with the Hellenic Institute of Marine Archaeology. Peloponnese and surrounding islands.

Oxford University, Oxford England

M.St. Maritime and Aegean Archaeology (with Honors- Magna Cum Laude) June 1991

Coursework includes: Ship and boat design, construction, and use, Aegean prehistory, maritime archaeology, classics and classical archaeology, scientific techniques in archaeology, computer applications in archaeology, philosophy of science. Advisor Professor Sean McGrail.

Reed College, Portland OR

B.A. Anthropology June 1988

Thesis: "The Ecology of Ships: Towards a Processual Theory in Underwater Archaeology." Advisor Professor Claude Vaucher.

Coursework includes: Archaeology, archaeological method and theory, ship design and construction, Indians, Eskimos and Aleuts, anthropology of magic, anthropological theory, political, classical and social philosophy, evolutionary, cellular, and molecular biology, humanities.

Texas A&M University, College Station TX

Archaeological Field School July-August 1987.

Coursework includes: Field excavation techniques, field conservation, report writing, archaeological documentation.

Work Experience:

Chief- United States National Park Service, Submerged Resources Center ; January 2010- Present. I manage a team of 9 archeologists, underwater photographers and support specialists in a small program that provides high-end boutique science for the National Park Service. Our mandate is world-wide and we provide regular scientific support for more than 200 units of the National Park Service. Our annual budget is approximately $2,200,000 and we are operationally involved in underwater operations and fieldwork in parks approximately 7 months per year.

Acting Regional Archeologist- United States National Park Service; Intermountain Region; November 2017-January 2018.

Acting Associate Regional Director (Cultural Resources)- United States National Park Service; Intermountain Region; January-March 2017.

Acting Chief- United States National Park Service, Submerged Resources Center; February 2009- January 2010.

Deputy Chief- United States National Park Service, Submerged Resources Center; June 2008-February 2009.

Underwater Archaeologist- United States National Park Service, Submerged Resources Center; August 2000-June 2008.

Chief Archeologist/Field Coordinator- The African Slave Wrecks Project, 2009-Present.

Principal Investigator/Science Coordinator- USS *Arizona* Project, 2008-Present.

Team Member/Logistics Lead- NPS Bioacoustic Project January 2016-Present.

Archeologist- Lake Mead Aggregate Plant Mapping Project. March 2020.

Field Director- Search for *L'Aurore*, Ihla de Mozambique, Mozambique. January-February 2020.

Field Director- USS *Arizona* Project. December 2019.

Field Director- San Francisco Maritime Museum Project. November 2019.

Archeologist- Lake Mead Aggregate Plant Mapping Project. October 2019.

Field Director- Dry Tortugas National Park Project. August 2019.

Field Director- Biscayne National Park Project. July 2019.

Archeologist- Lake Mead Aggregate Plant Mapping Project. March-April 2019.

Field Director- Biscayne and Dry Tortugas National Park Damage Assessment. February-March 2019.

Field Director- Slave Wrecks Survey, Mozambique. November-December 2018.

Archeologist- Lake Mead Aggregate Plant Mapping Project. October 2018.

Field Director- Slave Wrecks Project, Mozambique. July-August 2018.

Archeologist- Biscayne National Park Project. July 2018.

Archeologist- Lake Mead Aggregate Plant Mapping Project. March 2018.

Field Director- USS *Arizona* Project, December 2017.

Archeologist- Lake Mead Project, November 2017.

Field Director- USS *Arizona* Project September 2017.

Archeologist- DPAA Croatia Recovery Project, June-July 2017.

Field Director- USS *Arizona* Project, May 2017.

Archeologist- Midway Atoll, April-May 2017.

Archeologist- Slave Wrecks Project Buck Island National Monument, April 2017.

Archeologist- Ozark National Scenic Riverway, March 2017.

Field Director- USS *Arizona* Project, December 2016.

Archeologist- Lake Mead Project, November 2016.

Field Director- USS *Arizona* Project September 2016.

Archeologist- Buck Island National Reef/ Slave Wrecks Project, April-May 2016.

Archeologist- Youth Diving With a Purpose Biscayne National Park, July 2016.

Archeologist- Return to Antikythera Project, Antikythera Greece May-June 2016.

Archeologist- Return to Antikythera Project, Antikythera Greece September 2015.

Archeologist/Principal Investigator- Dry Tortugas Bioacoustic Project, July-December 2015

Archeologist- Dry Tortugas National Park, July 2015.

Archeologist- Saint Croix National Scenic River, May 2015.

Archeologist- Buck Island National Monument, April 2015

Archeologist/Principal Investigator- Glen Canyon National Recreation Area, March 2015.

Archeologist- Lake Mead B-29 September 2014.

Archeologist- Dry Tortugas National Park, July 2014.

Archeologist- Gulf Islands National Seashore; May 2013, May 2014.

Archeologist/Principal Investigator- Yellowstone National Park, May 2014.

Archeologist- Dry Tortugas National Park, July 2014.

Archeologist/Principal Investigator- SS *Rhoda* Investigation, Gulf Islands National Seashore May 2013.

Archeologist- HMS *Fowey* Investigation, Biscayne National Park, June 2013.

Archeologist- USS *Arizona* Project; December 2013.

Archeologist- USS *Arizona* Project; November 2012.

Archeologist/GIS Specialist- RMS *Titanic* Expedition; May 2010-2012.

Archeologist- Biscayne National Park Section 110 compliance survey; June-July 2012.

Archeologist- Gulf Islands National Seashore Section 110 compliance survey; April-May 2012.

Archeologist- African Slave Ships Project, Cape Town South Africa; December 2012.

Archeologist- Gulf Islands National Seashore Section 106 compliance survey; September 2011.

Project Director- Biscayne National Park BISC 002 Shipwreck Site Investigation; September 2011.

Archeologist/Project Director- USS *Arizona* Shipwreck Assessment; December 2010.

Archeologist- Lake Mead National Recreation Area Submerged Cultural Resources Assessments; November 2010.

Archeologist- Isle Royale National Park Shipwreck Assessments; September 2010.

Archeologist- Dry Tortugas National Park Shipwreck Assessments; July August 2010.

Project Director- Grand Portage National Historical Site; September October 2009.

Project Director- Shipwreck Site Assessments, Isle Royale National Park; September 2009.

Archeologist- NPS/NOAA/MMS Battle of the Atlantic Project; August 2009.

Project Director- Shipwreck Site Assessments, Dry Tortugas National Park, July 2009.

Project Director- *Walton Smith* Grounding Investigation, Biscayne National Park, June 2009.

Archeologist- USS *Arizona* 3-D Filming Project; February 2009.

Project Director- Lake Mead Fieldwork, Lake Mead NRA; April-May 2008.

Principal Investigator- *Walton Smith* and *Natalita* Grounding Investigations, Biscayne National Park, April 2008.

Project Assistant- Lake Mead B-29 3-D Filming Project, March 2008

Project Director- Lake Meredith Bathymetric Survey, February 2008.

Project Director- Montezuma Well National Monument, December 2007.

Project Director- Channel Islands Wreck Cruise, Channel Islands National Park, November 2007

Instructor- National Park Service 24-hour Dive Workshop, Lake Mead NRA, October November 2007

Archeologist/Co PI- West Loch Survey, Pearl Harbor Hawaii, August 2007

Project Director- Submerged Cultural Resources Assessment, Lake Mead National Recreation Area, June-July 2007.

Instructor/Course Designer- National Park Service Submerged Cultural Resources Law Enforcement Class Lake Mead National Recreation Area; February 2007.

Project Director- Lake Mead National Recreation Area PBY/Agg Plant Assessment; December 2006.

Archeologist- USS *Arizona* Project; June-July 2006.

Project Director- Lake Mead National Recreation Area Aggregate Plant/B-29 Assessment; January/February 2006.

Project Director- Montezuma's Well Assessment, Camp Verde AZ; January 2006.

Project Director- Hurricane Wilma Assessment, Biscayne National Park; December 2005.

Project Director- Missouri National Recreational River; October/November 2005.

Archeologist- Pearl Harbor Midget Submarine Assessment; August 2005.

Project Director- Fort Wadsworth Assessment, New York, NY; July 2005.

Project Director- Lake Mead Assessment, Boulder City NV; April/May 2005.

Deputy Project Director- Montezuma's Well Assessment, Camp Verde AZ; April 2005.

Project Director- Boston Harbor Clearance Assessment, Boston MA; August 2004.

Project Director- National Geographic Filey Bay Shipwreck Assessment, Filey Yorkshire, England, July 2004.

Deputy Project Director- Lake Pend d'Oreille Dugout Canoe, Sandpoint Idaho; April 2004.

Deputy Field Director- USS *Arizona* Assessment, Honolulu Hawaii; November 2003.

Project Director- Lake Mead B-29 Assessment. Boulder City NV; June 2003.

Project Director- Lake Mead B-29 Assessment. Boulder City NV; October/November 2002.

Project Director- Ellis Island Ferry Assessment, Ellis Island, New York August 2001-Present.

Deputy Field Director- USS *Arizona* Assessment, Honolulu Hawaii; June 2001, December 2001.

Underwater Archaeologist/Chief Field Archeologist- United States Naval Historical Center; March 1999-August 2000.

Field Director- National Park Service, *H.L. Hunley* Recovery; Charleston South Carolina May-August 2000.

Field Director- U.S. Navy *H.L. Hunley* Survey; Charleston South Carolina October-November 1999.

Field Director- U.S. Navy Penobscot River Survey; Bangor Maine; August-September 1999.

Field Director- U.S. Navy *H.L. Hunley/Housatonic* Survey; Charleston SC; May-August 1999.

Field Director- Ihla de Mozambique Survey; Ihla de Mozambique, Mozambique; March 1999.

Maritime Archaeologist/ Director of Research- The Hellenic Institute of Marine Archaeology, Athens Greece; September 1996-December 1997.

Maritime Archaeologist- United States National Park Service's Submerged Resources Center (formerly Submerged Cultural Resources Unit), Santa Fe New Mexico; March- September 1996.

Project Director/ Field Supervisor - Dry Tortugas National Park System-wide Archaeological Inventory Program; United States National Park Service, Dry Tortugas National Park, Florida; June-August 1996.

Nautical Archaeologist- *H.L. Hunley* survey, Charleston, SC April-June 1996.

Project Archaeologist- Loggerhead Reef Magnetic Anomaly Survey, United States National Park Service, Dry Tortugas National Park, Florida; July-August 1995.

Deputy Project Director- Shipwreck Site DRTO B016-032, United States National Park Service, Dry Tortugas National Park, Florida; June 1995.

Principal Investigator/ Director- Shipwreck Site DRTO-036, United States National Park Service, Dry Tortugas National Park, Florida; June-July 1994.

Principal Investigator/ Director- Shipwreck Site DRTO-036, United States National Park Service, Dry Tortugas National Park, Florida; June-July 1993.

Deputy Project Director- Hellenic Institute of Marine Archaeology, Island of Kythera, Greece; August- September 1997.

Project Archaeologist- Hellenic Institute of Marine Archaeology, Island of Kythera, Greece; September 1995.

Deputy Project Director/Field School Instructor- Hellenic Institute of Marine Archaeology, Cape Iria, Greece; July-August 1994.

Deputy Project Director/Field School Instructor- Hellenic Institute of Marine Archaeology, Cape Iria, Greece; July-August 1993..

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Team Member- Institute of Nautical Archaeology summer field school, Port Royal, Jamaica; July-August 1987.

Work Related Skills:

Diving: More than 3000 documented scientific research dives, 32 years of experience at depths to 348', NAUI open water 1, 2; NAUI Rescue diver; PADI Divemaster, NAUI Scuba Instructor, NAUI Nitrox, Underwater Investigator, IANTD nitrox diver, trimix diver, IANTD gas blender. UW photography and video, zero visibility, dry suit diving, ice diving, commercial surface supplied air diving, deep diving, medic first aid, DAN O2 provider, DAN O2 Instructor. Closed Circuit Rebreather, Closed Circuit Mixed Gas, AP Valves Inspiration and Evolution rebreathers, VR Technology Sentinel rebreather, XCCR rebreather, IANTD CCR cave diver, TDI CCR Cave and Cavern Diver, Normoxic CCR for both Sentinel and AP platforms. Hypoxic CCR for both AP and XCCR platforms.

Foreign Languages: French reading writing and speaking; modern Greek reading and speaking, some Italian, Spanish, and Japanese.

Boating: National Park Service training for boats up to 35' (MOCC certified), maritime safety, small craft operations, engine maintenance, lines and rigging.

Computers: Autocad, Arcview, ArcGIS (GIS), MS Office, Photo modeler, Photoshop and other image processing software packages, HYPACK and other marine survey software.

Instrumentation: Side-scan sonar, magnetometer, Roxann bottom classification device, remotely operated underwater vehicles (ROVs), GPS, sub-bottom profilers, vibracore geological specimen collectors.

Publications/ Professional Presentations:

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"The Curious Epistemology of Nautical Archaeology: Philosophical Reduction and New Knowledge Claims" Society for American Archaeology Annual Meetings, Seattle Washington, April 1998.

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"Metoric: The Rhetoric of Paradigmatic Confrontation in Archaeology" Radical Archaeology Theory Seminar, Binghamton, New York April 1994.

Honors and Fellowships:

M.St. with Distinction (high honors)- Oxford University, May 1991

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Joukowsky Award Nominee for best university dissertation, Brown University, May 1999

Watson Smith Prize, Anthropology Department, Brown University, May 1998

Associate Member-American School of Classical Studies- Athens, Greece 1996-1997.

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Investigating archaeological site formation processes on the battleship USS *Arizona* using finite element analysis

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ABSTRACT

Scientists from the National Institute of Standards and Technology (NIST) worked in a collaborative partnership with archaeologists from the National Park Service's (NPS) Submerged Resources Center (SRC) to develop a finite element model (FEM) of the battleship USS *Arizona*. An FEM is a computer-based engineering model that calculates theoretical stresses, propagation of force, and shape changes to a structure under loads using thousands or even millions of individual elements whose individual responses are well understood. NIST researchers created an FEM of an 80 ft. (25 m) midships section of the *Arizona* site to analyze archaeological site formation processes on the sunken battleship, in particular to determine the current condition of the wreck and predict its future strength and structural integrity as it continues to corrode. The NIST's FEM study is one aspect of a larger project under the direction of the NPS, the USS *Arizona* Preservation Project, whose goal is to determine the nature and rate of corrosion affecting USS *Arizona*, and to model its long-term structural deterioration. The FEM incorporates findings from other key components of the USS *Arizona* Preservation Project, such as steel hull corrosion rates, structural surveys of the vessel, sediment compaction studies, and analysis of the concretion that covers the ship's hull, into a single tool that is being used to predict how the wreck will degrade in the future.

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1. Introduction

Scientists from the National Institute of Standards and Technology (NIST) worked in a collaborative partnership with archaeologists from the National Park Service's (NPS) Submerged Resources Center (SRC) to develop a finite element model (FEM) of the sunken battleship USS *Arizona*. The *Arizona*, which was sunk on December 7, 1941 and is a symbolic touchstone of America's entry into World War Two, still contains nearly 600,000 gallons of fuel oil within its corroding hull. The USS *Arizona* has been designated a National Historic Landmark—the highest level of national historic significance in the United States—and is administered cooperatively by the NPS and U.S. Navy. It is among the most recognized and visited war memorials in the United States. Nearly a million and a half visitors annually make the short trip across Pearl Harbor to the USS *Arizona* Memorial, which spans the battleship's sunken hull.

An FEM is a computer-based engineering model that calculates stresses, propagation of forces and shape changes to a structure under loads using thousands or even millions of individual simple elements, whose individual responses and interactions are calculated and combined into an aggregate model of the structure. We created an FEM of an 80 ft. (25 m) midships section of the *Arizona* site to analyze archaeological site formation processes on the sunken battleship, in particular to determine the current condition of the wreck and predict its future strength and structural integrity as it continues to corrode. The NIST's FEM study is one aspect of a larger project under the direction of the NPS, the USS *Arizona* Preservation Project, whose goal is to determine the nature and rate of corrosion affecting USS *Arizona*, and to model its long-term structural deterioration (Murphy and Russell, 2008; Russell et al., 2004). The FEM incorporates findings from other key components of the USS *Arizona* Preservation Project, such as steel ull corrosion rates, structural surveys of the vessel, sediment compaction studies, and analysis of the concretion that covers the ship's hull, into a single tool that is being used to predict how the wreck will degrade in the future (Johnson et al., 2000, 2006a,b; Makinson et al., 2002; Russell et al., 2006; Storlazzi et al., 2004, 2005).

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Beginning in 2001, the NPS-SRC designed the USS *Arizona* Preservation Project to be multi-year, interdisciplinary, and cumulative, with each aspect of the project contributing to overall research questions. Principal investigators and resource managers planned the USS *Arizona* Preservation Project to provide a broad-based foundation for preserving, managing and monitoring the sunken battleship by building upon initial documentation and corrosion research on the *Arizona* site led by the NPS-SRC in the 1980s (Henderson, 1989; Lenihan, 1989; Lenihan and Murphy, 1989) (Fig. 1), as well as pioneering research into the corrosion of iron and steel archaeological materials underwater by investigators in Australia (e.g. MacLeod, 1982, 1989, 1995, 2002; McCarthy, 1988, 2000; North, 1976; North and MacLeod, 1987). Our primary project focus was to acquire requisite data for understanding and characterizing the complex corrosion and deterioration processes affecting *Arizona*'s hull, both internally and externally, and to model and predict the nature and rate of structural changes resulting from corrosion.

Addressing questions about corrosion nature and rate, as well as long-term structural integrity, is required to make informed management decisions for long-term preservation and to minimize environmental hazard from ongoing fuel oil release (Cummins and Dickinson, 1989). Developing reasonable and effective management alternatives and deciding the most desirable actions, particularly those regarding intervention or rehabilitation, cannot be effectively accomplished without this information. The current research program is a critical step in obtaining necessary scientific information upon which to make sound management decisions. A central goal of this research entails developing and recommending short-term and long-term management plans for site preservation based on the results of the research program (Cummins and Dickinson, 1989). In addition, we intended the project to serve as a model for interdisciplinary, science-based management of underwater cultural heritage that has direct application for studying historical iron and steel vessels worldwide (e.g. Wilson et al., 2007).

The USS *Arizona* Preservation Project addresses another important issue besides preservation of an internationally important site. USS *Arizona* likely contains nearly 600,000 gallons of fuel oil that has been slowly escaping since its loss in 1941. This oil, a potentially serious environmental hazard, is contained within the corroding hull. Results to date, especially from the FEM, indicate that catastrophic oil release is by all indications not imminent. Understanding the complex hull corrosion processes, structural changes, and oil release patterns, however, offers the most effective and efficient method of mitigating this potential hazard over the long-term. One of the goals of this project, therefore, is to develop a research strategy for environmental impact risk assessment and abatement to address the oil containment issue (Russell et al., 2004).

Because of the particular national importance of USS *Arizona*, any solution to the oil issue must incorporate a minimum impact approach so that long-term site preservation will not be compromised (Delgado, 1989, 1992; Linenthal, 1991; Vesilind, 2001). Unnecessary disturbance to *Arizona*'s hull is likely to be seen by many as more problematic than the limited oil release now occurring. In addition, we conducted all research and monitoring operations with the respect due to an American war grave and with minimum impact to the site consistent with NPS principles of stewardship and preservation (Russell and Murphy, 1997). In practice this means that divers did not enter the ship, which is effectively a tomb for more than 900 sailors and marines who died during the attack, and we have had very limited access to the interior spaces of the sunken vessel. Addressing the oil release problem within a site preservation framework provides the best balance between the competing social values of preservation and ecology, and it has the highest probability of arriving at the optimal solution for both issues. Managers will ultimately have to face the possibility of a larger release, although there is already an extensive oil recovery capability staged at Pearl Harbor (an active United States Navy base), and a contingent of practiced professionals stand ready as a response team for oil spills.

2. Finite element analysis

One of the USS *Arizona* Preservation Project's most important questions was how the cumulative results of *Arizona* research could be used for modeling and predicting long-term site formation processes, particularly changes in the hull, and, more specifically, how and when those changes would occur. A finite element analysis (FEA) was the principal research method chosen to produce a predictive tool that forms the centerpiece of USS *Arizona* research.

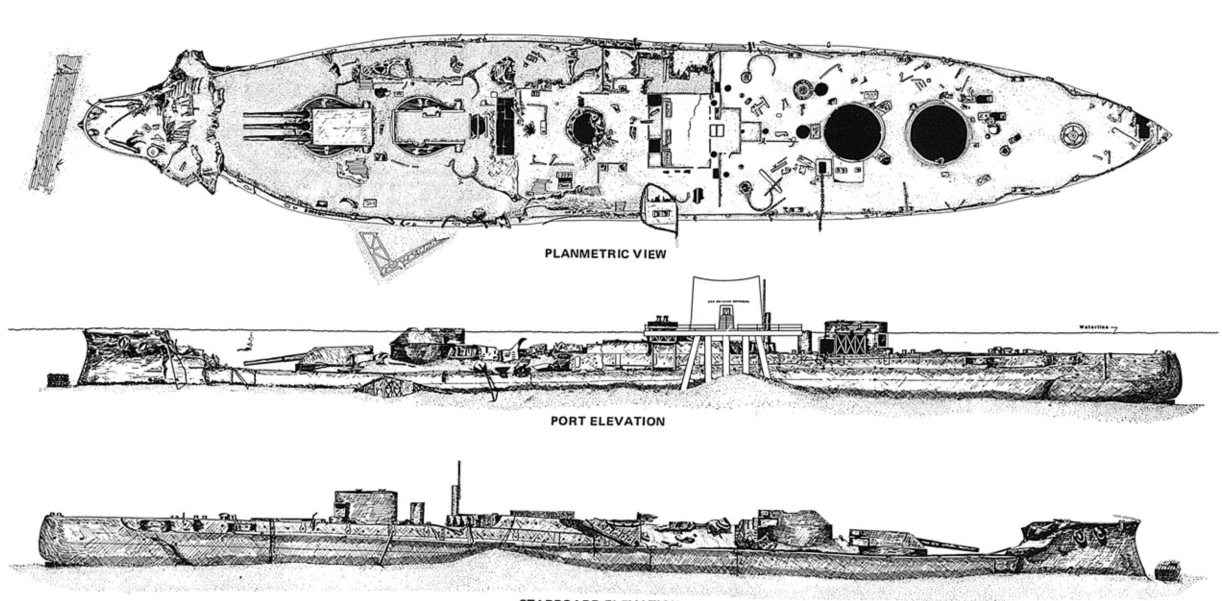

Fig. 1. Map of the USS *Arizona* site completed by the National Park Service in 1985 (NPS-SRC drawing).

An FEA begins with development of a finite element model (FEM), a computer-manipulated mathematical model that calculates theoretical stresses and shape changes in a structure under load using experimental variables based on observationally-derived data. In anthropology, FEA have been most commonly used by biological anthropologists to model evolution of primate physiology (see, e.g., Hernandez et al., 2009; Kupczik, 2008; Kupczik et al., 2009; Richmond, 2007; Strait et al., 2007). Application of FEA within the field of archaeology is rare, but has recently been used to model the mechanical properties and performance characteristics of archaeological ceramics (e.g. Hein et al., 2008; Kilikoglou and Vekinis, 2002). A variety of recent literature reviews the fundamentals of archaeological site formation processes on submerged sites (e.g. Gibbs, 2006; O'Shea, 2002; Quinn, 2006; Stewart, 1999; Ward et al., 1999), however FEA has not been applied to modeling site formation processes on submerged archaeological sites or other underwater cultural heritage (although the Civil War submarine *H.L. Hunley* was subjected to a pre-recovery FEA to determine if the hull would withstand recovery, see Oceaneering International, Inc., 2000). While FEA has had some application to historical ships studies, such as hypothetically modeling the sinking of RMS *Titanic* (e.g. Felkins et al., 1998; Foecke, 2008; Hooper et al., 2003a,b), it has not been previously used to assess long-term preservation of historically-significant shipwreck sites like USS *Arizona*.

The FEM mathematically divides a complex solid into many thousands of smaller components called *elements*, each of which can be one of numerous simple shapes. Each element is given a location, a proximity to other elements, its own mechanical properties such as strength and brittleness, details about how it is connected to its neighbors, how it is allowed to deform and move and how it transmits stresses to adjacent elements. Properties for the material of each element are input into computer software that describes the element's behavior between its end (or finite) points (for example, mechanical properties, heat flow, density, etc.). The end points of each "finite" element are called *nodes*. Once the structure is built of these elements in the computer, conditions are set regarding how nodes connect to one another, and loads and fixed points (known as boundary conditions) are added to the model to restrain movement. As each individual element changes under different boundary conditions, it transmits a slightly changed condition to neighboring elements, which then adjust themselves in response, and so forth through all the elements of the model. The results of the model are predictions of the deformations and deflections that will result from that loading, as well as predictions of the stresses that each element, and thus each piece of the body, will experience. These results are displayed as plots of displacements of nodes and calculated stresses in the structure at all points. Taken in the aggregate, the displaced nodes and stresses of all the elements in the FEM offer a predictive model of stress and change under different conditions for an entire structure.

For an historical shipwreck such as USS *Arizona,* an FEA allows manipulation of multiple variables, such as corrosion rate and hull thickness, to analyze loads and stresses on the hull structure for predicting structural displacement, probable collapse rate, its nature, sequence and consequent impact on structures containing fuel oil. In addition, the FEM provides a fundamental tool to evaluate consequences of proposed management alternatives involving structural intervention or preservation strategies.

There are particular difficulties in applying FEA to shipwrecks, however. Geometry is constantly changing due to ongoing corrosion, loads can be very complex, and loads and corrosion interact in such a way as to increase the complexity of the model (for example from processes such as stress corrosion cracking). There are ways to overcome these difficulties, but accurate data based on direct measurements and observations are of primary importance. For the model to be representative of actual conditions, input data such as structural dimensions and connections, corrosion rates and loads must be as precise as possible.

Predictions about current status and future collapse resulting from the FEA will vary in accuracy depending on the detail of the input data, crafting the correct boundary conditions, and by minimizing simplifying assumptions. For the first issue, the greatest deficiency in data in this case was our knowledge of the current thickness and condition of hull features both internally and below the present harbor bottom. We could not directly measure the present condition of those areas like we could the external portions of the hull above the harbor bottom. All other assumptions and simplifications have a much smaller effect on the results than these data. The boundary conditions—the external constraints that limit the scope and extent of the FEM—were similarly difficult, as the hull is supported by a water-saturated, semi-solid harbor bottom that moves relative to the hull.

As the primary "product" of the current research program, much of the data collected during field work and as a result of the ongoing monitoring of USS *Arizona* was designed to be fed directly into revising and refining the FEM to make it as accurate as possible. An accurate corrosion rate of *Arizona*'s steel hull is a key ingredient in an FEA that can be extended into the future to determine how and when the vessel will loose critical structural integrity and begin to collapse. Field investigations and laboratory research whose goal is to determine corrosion rates on various hull components, both internally and externally, as well as above and below the harbor bottom, has been one of the most important aspects of the USS *Arizona* Preservation Project (Johnson et al., 2006a,b; Makinson et al., 2002; Russell et al., 2006). When combined with accurate corrosion rates and other variables, however, the FEA provides predictability required for evaluating the timing, necessity, and long-range consequences of current and future management actions.

During long-term monitoring of *Arizona*'s structure over time, if observed change conforms well with changes predicted by the FEA, researchers will have confidence in extending the model's predictions to areas of the ship that are difficult to access directly for monitoring purposes, such as the lower decks. If observed changes do not accord well with the predictions of the FEA, the disjunction between real and predicted behavior will alert researchers to modify the FEM, gather new data that may have been overlooked in the initial model, or both. Over the course of this investigation (and afterwards), we anticipate a dynamic give and take between the FEA and ongoing research.

3. Building the model

Limitations in funding and available resources did not allow us to model the entire hull at this time. Rather than model the entire ship at a much coarser level, we instead chose a representative section of the ship to model with higher precision. We developed a baseline FEM of USS *Arizona* by modeling an 80 ft. (25 m) cross-section of hull structure amidships, between frames 70 and 90 (*Arizona* was built with frames on 4 ft. [1.2 m] centers, numbered beginning at the bow and moving aft—thus, frame 70 is 280 ft. [85 m] aft of the bow) (Fig. 2). We chose the 80 ft. section of hull between frames 70 and 90 for our FEM for three primary reasons. First, because it is likely that oil containment spaces in the forward sections of *Arizona*'s hull were destroyed in the blast that sank the vessel during the aerial bombing of Pearl Harbor on December 7, 1941, the modeled section is the forward-most part of the hull that may have intact oil bunkers. From frame 70 aft, the ship's hull is

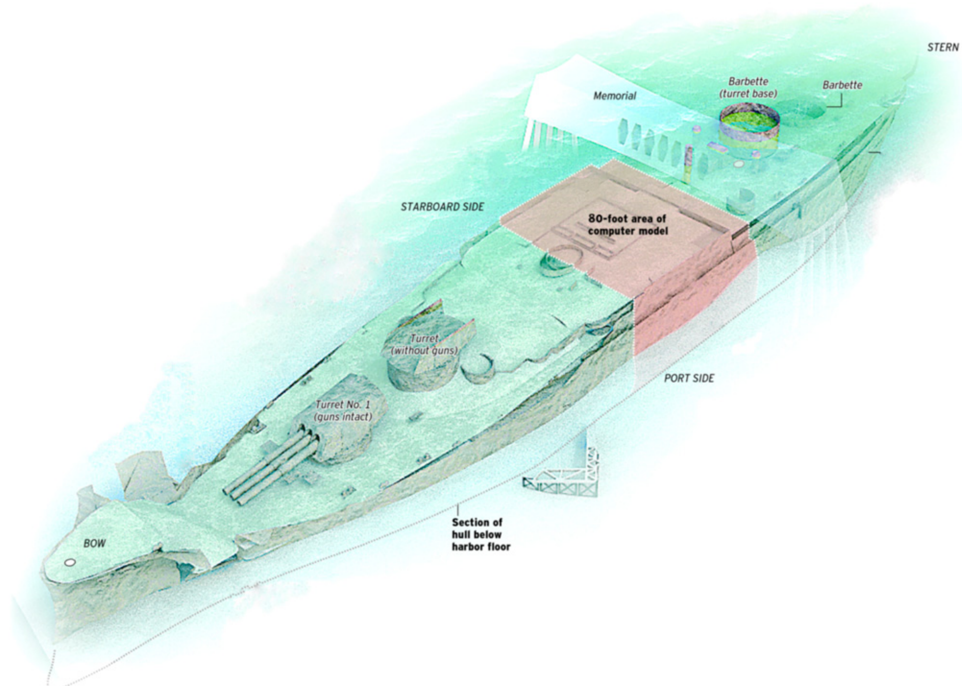

Fig. 2. The 80-ft. (25 m) section of USS *Arizona*'s hull modeled for the finite element analysis (graphic courtesy of Shaffer Grubb/San Diego Union-Tribune).

intact and oil containment spaces were likely undamaged during the attack—results from the FEA can therefore be applied to the rest of the ship with intact oil containment spaces. Second, we selected the closest intact hull section adjacent to the explosion that sank *Arizona*—the section of hull we chose to model is directly aft of the most heavily-damaged portions of *Arizona*'s hull (Fig. 3). In addition to possible blast damage, this portion of the ship's hull was engulfed in fire for nearly 3 days subsequent to the ship's sinking, which may have changed the structural characteristics of the ship's fabric. We believe that applying an FEA to this section of the ship will give us a conservative estimate of overall hull deterioration because corrosion in this area is likely higher than undamaged areas of the ship due to its proximity to the massive explosion that sank the vessel and the subsequent fire. By modeling this portion of the hull we incorporated a conservative, worst case, perspective into the FEM, and we can therefore apply results of the study to the battleship's aft half, which is in better condition than the bow section and contains the bulk of the remaining oil, with greater confidence. Third, although each area of *Arizona* is different from others, this region of the ship is primarily composed of engine spaces below and working spaces above and it is free from massive structures such as main gun barbettes that would make the results of the FEA more difficult to generalize to other regions of the ship. Because FEA has not been applied to corrosion and deterioration of an historical shipwreck before this study, we believe this preliminary model also allows us to refine and test methodologies before developing the more complex and costly overall model required for predicting present and projected future structural strength of the entire hull.

The first stage of the FEM process was to create a detailed, three-dimensional mesh of the 80 ft. (25 m) midships section of *Arizona*'s hull in its pre-sinking state. Although *Arizona* was originally launched in 1915, it underwent a major refit in 1929–1931. To create the initial mesh, we used construction plans and blueprints from the 1929 to 1931 refit to make the *Arizona* FEM as accurate as possible. For the purposes of the FEM, we assume natural degradation of the hull steel during the battleship's operational life was negligible. We used as many blueprints of *Arizona*'s design as available that showed the main construction details and layout of the load-bearing elements and interior spaces. Many more drawings of the smaller details of junctions and fittings were not used, as at the scale of the model the connections between major parts of the ship would need to be idealized and not modeled down to the rivet-level. Unfortunately, several pieces of information regarding the internal configuration of the ship, particularly the detailed placement of floor beams and wall columns and their dimensions, were not found in the drawings. Transverse sections of the ship at frames 75 and 93 gave some finer structural details (Figs. 4 and 5), and these combined with the individual deck plans and the midships longitudinal section (Fig. 6) allowed us to make reasonable assumptions about the location and dimensions of all load-bearing components. As mentioned, the connections between these components were idealized to speed running of the model. In effect, the component connections were entered as if the two components being joined were simply made of one piece of metal. Because riveted connections are designed to be stronger than either constituent that makes up the joint, this is a reasonable assumption. The steel of the hull and structure was modeled as an isotropic elastic plastic continuum (i.e., a uniform but stretchable and moldable structure), that ranged in physical properties from complete failure to the strength and characteristics of the original battleship steel. The values of specific properties used (density: 7800 kg/m^3, Young's modulus: 200 GPa, Possion's ration: 0.3, yield stress: 309 MPa, ultimate stress: 563 MPa) are all standard literature values or measured using tensile tests on samples of steel taken from *Arizona* for this study.

The final stage of FEM development incorporated data collected during other aspects of the USS *Arizona* Preservation Project to complete the model of *Arizona*'s present condition and to allow us to extend the model into the future. Details from archeological surveys of the wreck that showed broken structural connections, missing deck plates and any other damage to the load-bearing

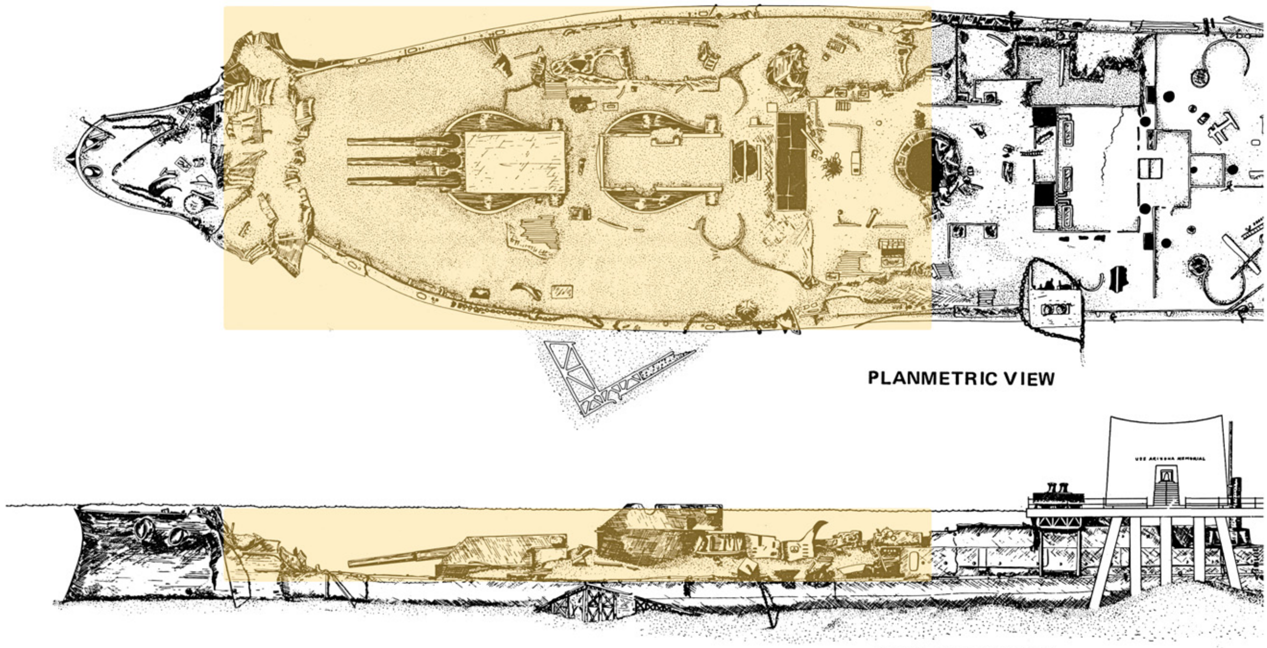

Fig. 3. The area of USS *Arizona*'s hull most directly impacted by the explosion that sank the vessel on December 7, 1941 (NPS-SRC graphic).

structures were added as modifications to the pre-sinking design in the model. The viscoplastic properties of the sediment in which the wreck sits have been measured by the U.S. Geological Survey (USGS). These properties were used in the model as part of the lower boundary condition, where the steel of the outer hull was in contact with the mud, allowing both load transfer and for the mud/steel interface to slip as the ship settles and deforms. The concretion on *Arizona* has been found to have a fairly dramatic impact on the decay and eventual collapse of the wreck. The layer of biomass, shells, mud, sand and corrosion product that is encasing the wreck has been studied. The encrustation layer, while stiff and fairly hard, is also quite brittle, with the constituents being poorly bonded to both each other and the surface of the steel. While the concretion has the overall effect of slowing the corrosion process as

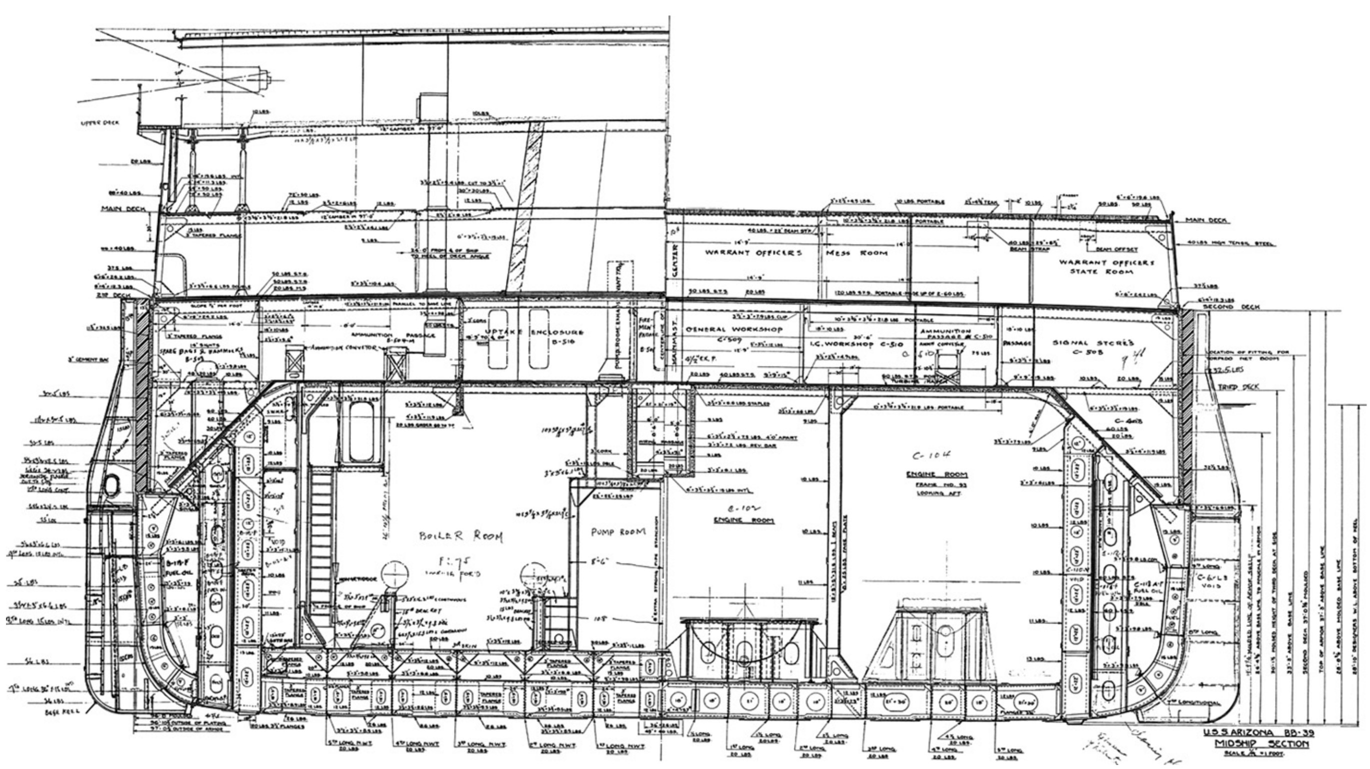

Fig. 4. USS *Arizona* vessel plans showing a composite cross-section of frame 75 looking forward (left) and frame 93 looking aft (right) (USS *Arizona* Memorial Archive).

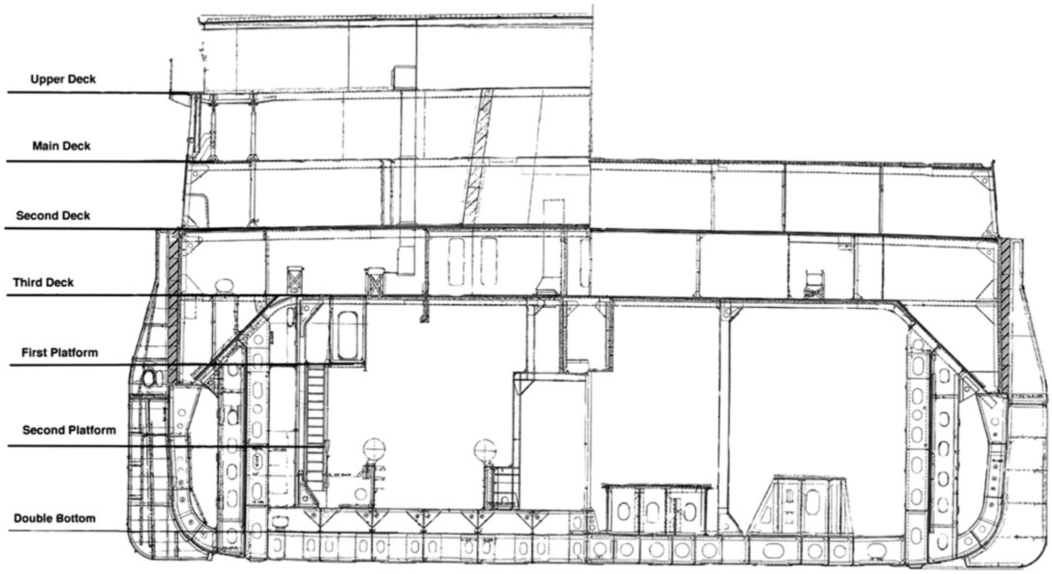

Fig. 5. Vessel plans from Fig. 4 cleaned by NIST for easier input into the finite element model, with deck levels indicated (NIST graphic).

it limits access of oxygen to the steel hull (a factor taken into account when measuring corrosion rates), the effect of the encrustation on the FEM is the weight and subsequent stress that it puts on the surviving hull. As the wreck's steel components corrode, they lose thickness and weight. But overall the encrustation grows faster than the steel corrodes, and thus over time the wreck gains mass. This deadweight must be added to the weight of the steel itself, and it is the weight of both together that is driving the collapse of the wreck.

To facilitate changes in properties and/or boundary conditions within the model, the FEM was divided into zones, or collections of elements, that could have their properties changed in unison.

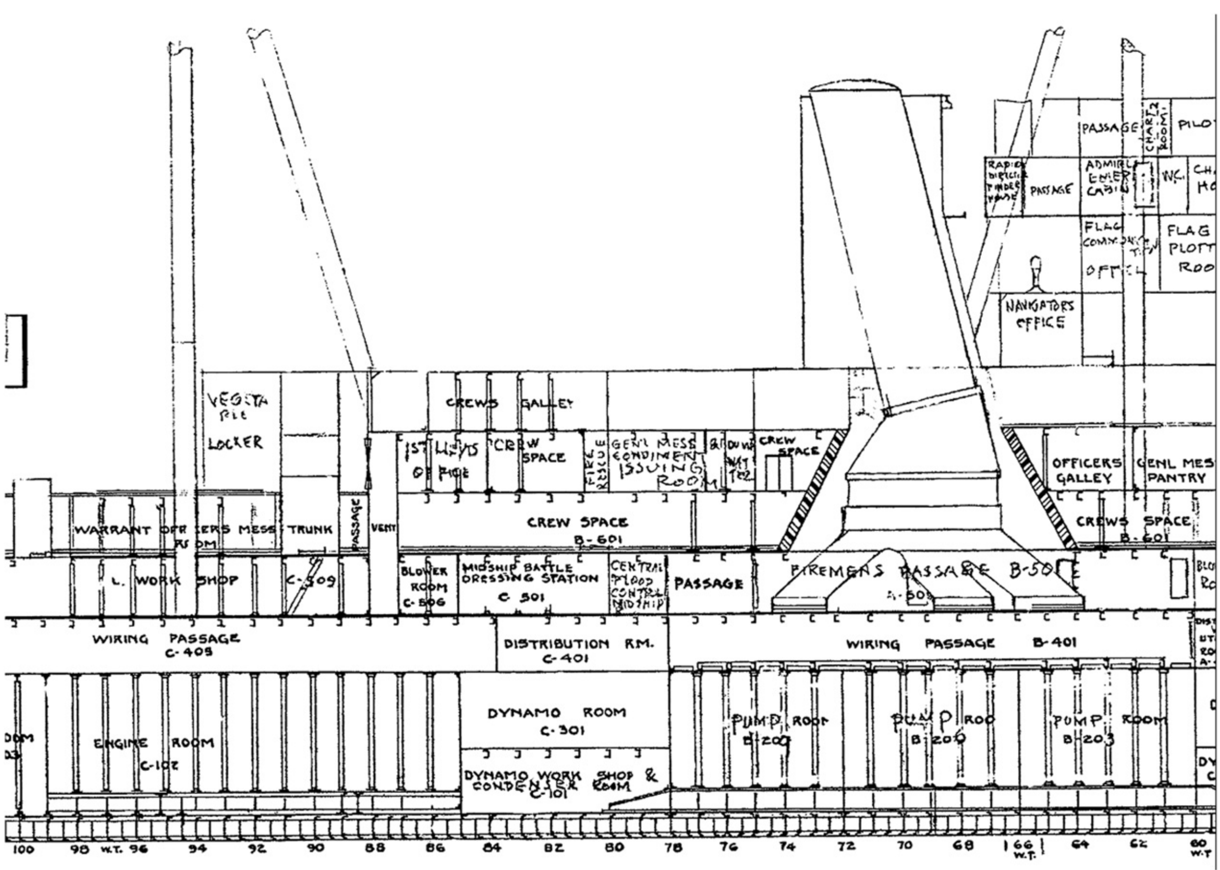

Fig. 6. Midsection cutaway of USS *Arizona*'s hull from frame 60 to 100, showing beams and girders (USS *Arizona* Memorial Archive).

Empirically we have determined that corrosion rates covary closely with water depth and this allowed us a basis for setting zones in the FEM. These generally consisted of pairs of decks within the structure, as the main parameter to be varied is the density, reflecting changes in corrosion in the steel plates and members at different water depths and under the harbor bottom, and thus differences in steel thicknesses.

The model was meshed at a level of detail seen in Fig. 7. The model contains approximately 57,000 elements and 255,000 degrees of freedom. It is important to note that the great majority of the work in creating an FEM of a structure is in the generation of the model and mesh in the computer. Remediation scenarios can then be tested and further stability studies can be made by simply changing the inputs and accounting for new measurements, ideas or to test other scenarios. After initial runs of the FEM, if certain areas of the model were found to not converge to a satisfactory result, the area was re-meshed more finely until the solutions converged. If there were areas that did not show large changes in stress as the ship corroded, these could be simplified as coarser elements, which saves computational time.

Once the model is developed in geometry and element placement, a definition of the boundary conditions is imposed (Fig. 8). The open ends at frames 70 and 90 were constrained from motion along a line parallel to the long axis of the ship. The steel elements in contact with the first layer of mud elements were prescribed to remain in contact as both are allowed to deform. The mud bottom supporting the lower hull was proscribed as a large enough entity that any movement and deformation of the lower hull that occurred in the model was still mediated by the supporting mud matrix. The boundary of the mud was constrained from motion in all three axes. Each element was given a weight with a density that can be independently set or changed as part of a zone, and the surfaces of the elements were allowed to bear additional loads from the concretion.

A major limitation of the FEA involves the fact that the geometry of the body being studied is fixed, while the loads, boundary conditions and material properties are changed, to study how a design performs under different conditions. This works very well for design issues, which is where FEA is commonly used. In the present study, the inverse problem is being studied: the loads and material properties are fixed, while the geometry is changing with time due to corrosion of the steel. Under ordinary circumstances, the entire model would need to be re-meshed with the new measurements for every state of the wreck to be studied. In order to be able to run a parameter study, where the variables that can be changed are varied in a systematic way to evaluate the stability of the system, a model was developed where the density of the elements was changed.

The critical parameter in this study is the stress that any given component experiences under the weight of itself, what it is attached to, and the concretion. Stress loads are modified by the cross-sectional area of the element that it is propagated to and from, so for example a small load propagated through a relatively small cross-section produces high point loads while a large load propagated through a large cross-section produces relatively low point loads and therefore less point stress in the model. The stress increases if the area decreases (due to corrosion) or the load increases (due to, in this case, increasing density). Using this technique, the physical dimensions of the element are kept constant, but the density is increased so that the stress in the component increases as it "thins" in the model.

4. Results

It is perhaps most illustrative to present the results from the model in chronological order as the wreck decays, describing issues that develop and warrant examination. The rate of steel corrosion is taken directly from data collected on the USS *Arizona* site—corrosion rates of exposed hull fabric above the harbor bottom are approximately three times faster than those buried below the harbor bottom. In the figures to follow, stresses are shown in a color scale ranging from dark blue through green, yellow, orange and red. These correspond to stress levels of less than 10% (dark blue), 10–25% (green), 25–50% (yellow), 50–75% (orange), and more than

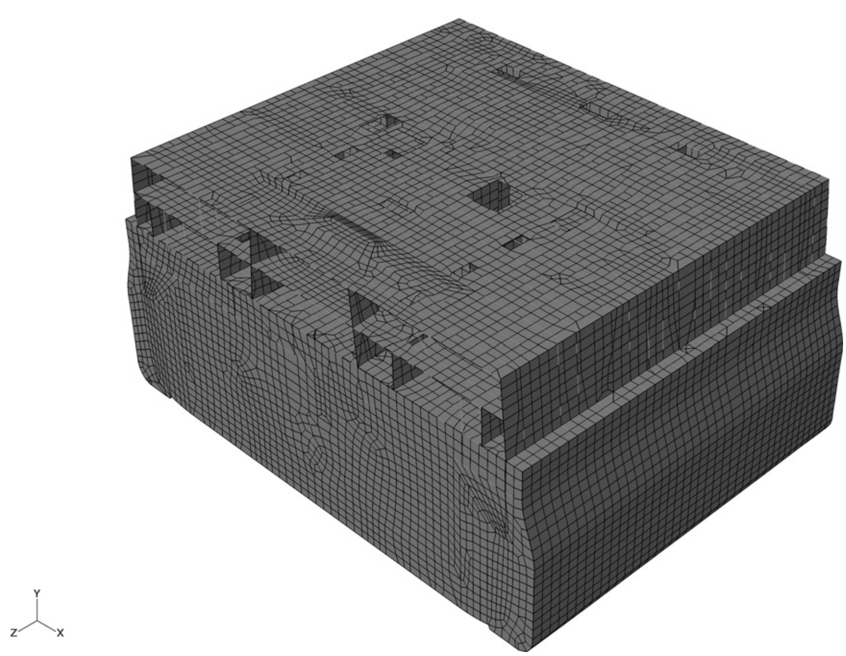

Fig. 7. Image showing the level of meshing on the finite element model. The model contains approximately 57,000 elements and 255,000 degrees of freedom, roughly equivalent to the NIST models of the collapse of World Trade Center towers 1 and 2 (NIST graphic).

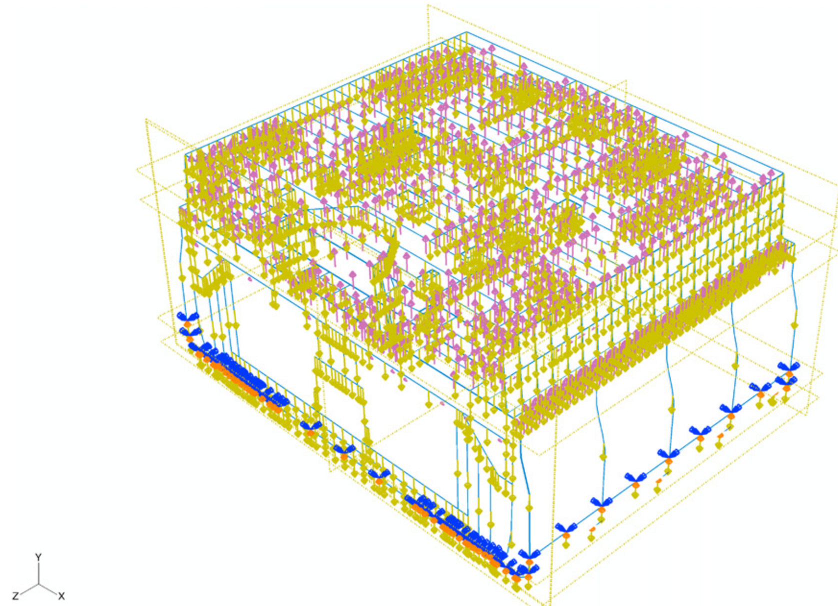

Fig. 8. Diagram of boundary conditions and loadings in the model. Gold = weight; purple = encrustation; blue = no longitudinal motion; orange = support from harbor bottom sediments (NIST graphic).

75% (red) of the breaking stress of the steel, respectively. Once an element has reached its breaking stress, it is defined as having no strength in the model, and is removed. The results presented are those where the steel exposed above the harbor bottom is allowed to degrade three times faster than the buried steel, which appears from corrosion analysis to be a reasonable scenario. We determined the approximate equivalent dates for each level of degradation of *Arizona*'s hull by assuming a linear corrosion rate from 1941 through 2002 (when we actually measured steel hull thickness and calculated the corrosion rate), and extrapolating into the future. Since the corrosion rate is most likely non-linear, being affected by many factors such as the presence and thickness of the encrustation, this is only an approximation that will need to be refined in future work.

The pre-sinking model indicates the computed stresses when dimensions of the ship are taken directly from the design blueprints (Fig. 9). The stresses everywhere are very low, which is to be expected as this is a warship and it was considerably overbuilt to be able to withstand battle damage. The stresses are higher in the vertical walls in the lower levels, as expected, since these walls are supporting much of the weight of the ship above.

The equivalent of 10% loss of steel from corrosion, which was projected to occur by the year 1980 based on calculated corrosion rates, shows the stress distribution is very similar to the pre-sinking

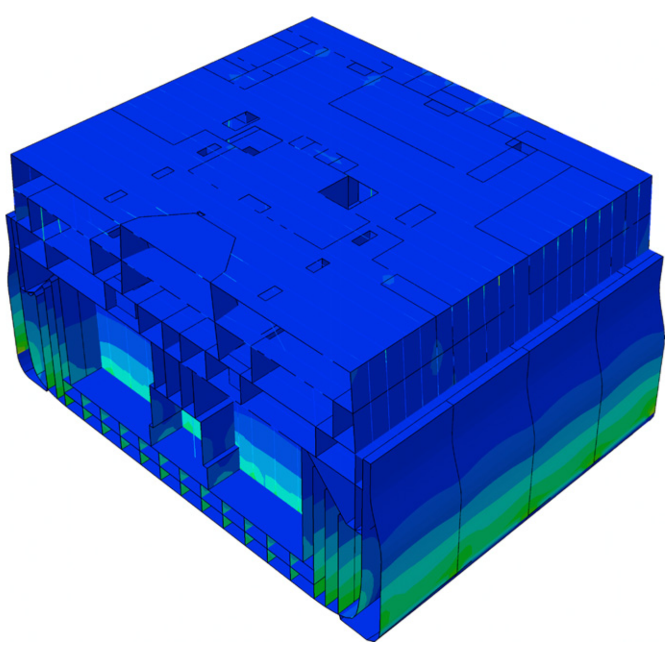

Fig. 9. Weight stress in pre-sinking condition (NIST graphic).

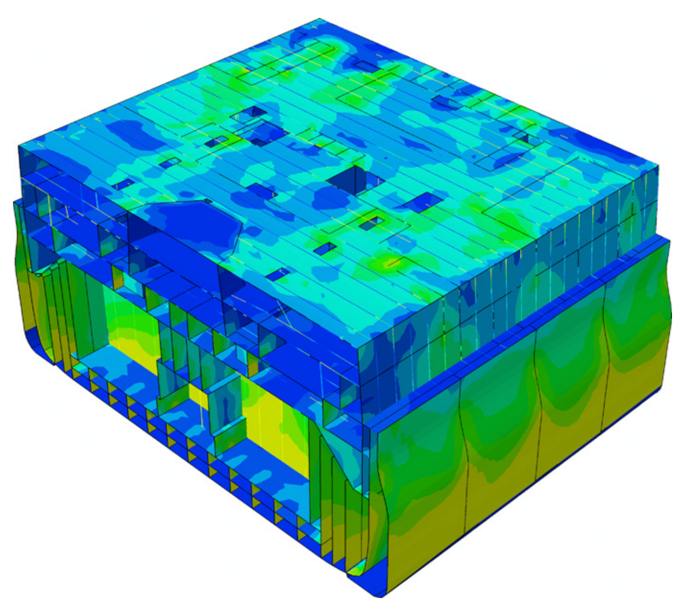

Fig. 10. Weight stresses after 10% thickness loss due to corrosion, approximate date = 1980 (NIST graphic).

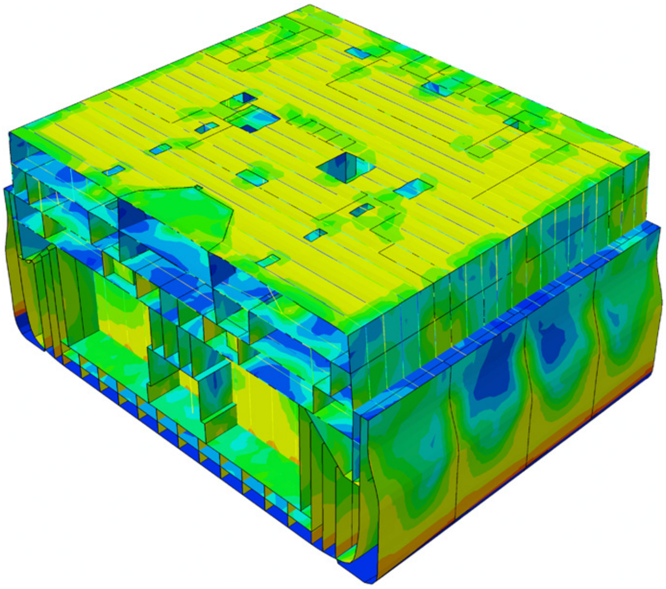

Fig. 11. Weight stresses after 20% thickness loss due to corrosion, approximate date = 2020 (NIST graphic).

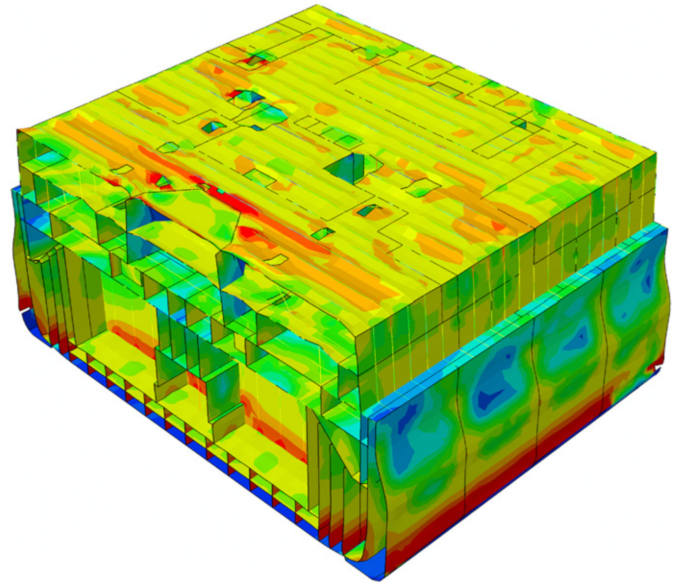

Fig. 13. Weight stresses after 50% thickness loss due to corrosion, approximate date = 2120 (NIST graphic).

condition, but with the overall stress levels somewhat higher. It is noteworthy that the deck beams in the upper deck have jumped significantly in stress, and the second, first and main decks remain almost unstressed (Fig. 10).

When the hull reaches 20% loss of steel from corrosion (projected to occur by the year 2020 based on calculated corrosion rates), the upper deck shows sagging beams and deck plates as hull members continue to thin. Stresses at the turn of the bilge of the torpedo blisters are approaching the tensile strength of the steel, while stresses in the vertical members continue to increase (Fig. 11). The present (2009) state of the *Arizona* site is assumed to be at this level of degradation, and indeed the upper deck presently shows some sagging and limited collapse as predicted by the FEM.

At an estimated 30% loss of hull steel (projected to occur by the year 2050), the turn of the bilge area of the torpedo blister, as well as the connections of the lower bulkheads to the hold platform are very close to critical. There is additional sagging in the upper deck, as well as increased stresses in the bulkheads of the lower deck (Fig. 12).

When 50% of the hull steel is lost due to corrosion (projected to occur by the year 2120), localized collapse events begin to appear, including portions of the torpedo blisters, double bottom vertical wall segments, upper deck beams and the region around the stack armor, undoubtedly collapsing under the weight of this very thick steel (Fig. 13).

A 60% loss of steel due to corrosion (projected to occur by the year 2150), there is general collapse of the deck plating on the

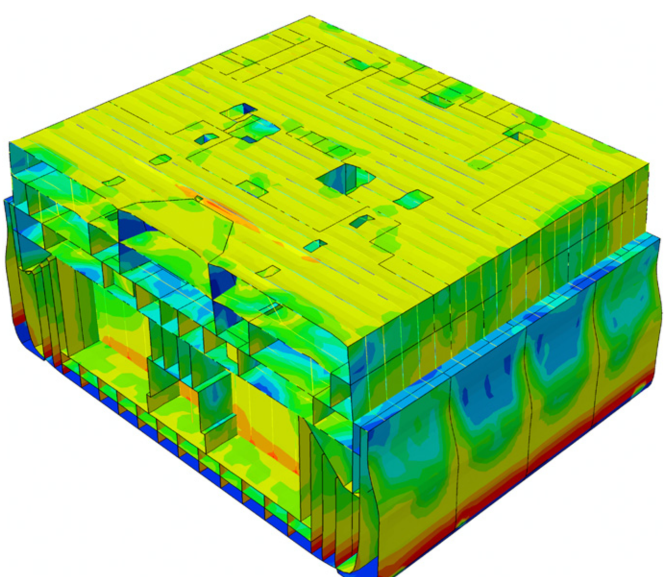

Fig. 12. Weight stresses after 30% thickness loss due to corrosion, approximate date = 2050 (NIST graphic).

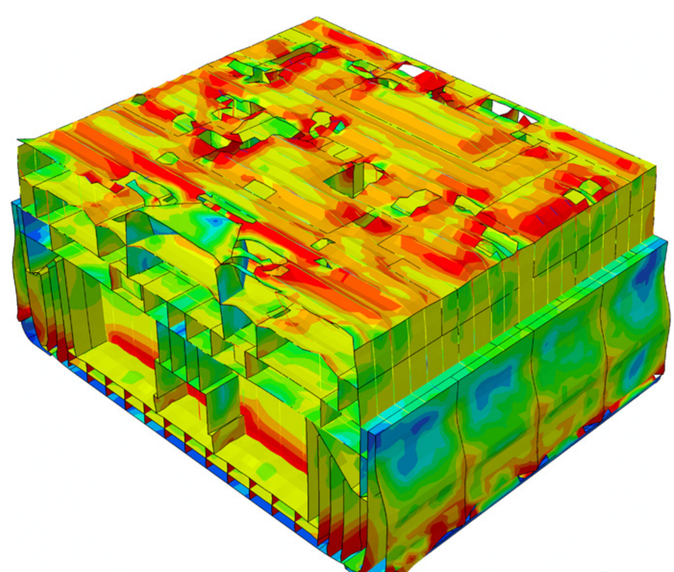

Fig. 14. Weight stresses after 60% thickness loss due to corrosion, approximate date = 2150 (NIST graphic).

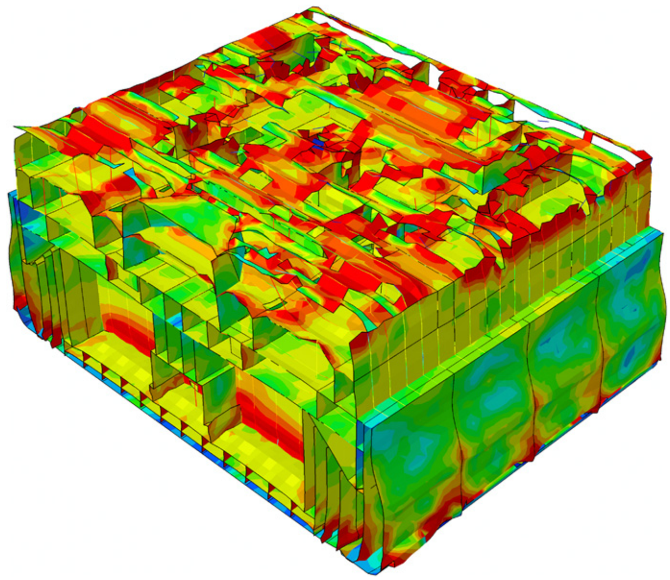

Fig. 15. Weight stresses after 70% thickness loss due to corrosion, approximate date = 2180 (NIST graphic).

upper and main decks, collapse of the outer hull plating and torpedo blisters, and very high stresses in the bulkheads at the hold platform in the engine spaces. Buckling of the hull shell plating begins (Fig. 14).

The upper deck is unrecognizable after a 70% loss of steel (projected to occur by the year 2180), and much of the deck plating and deck beams have fallen and accelerated the collapse of the main deck and those further below. The hull shell and torpedo blister continue to collapse, as well as the double bottom (Fig. 15).

When the hull steel reaches 90% loss due to corrosion (projected to occur by the year 2240), the decks of the superstructure (upper, main, and second decks) are expected to collapse further and pancake onto the third deck. The double bottom will completely collapse. Importantly, however, the core cylinder of the wreck, consisting of the volume bounded by the third deck, the inner bottom and the side oil tanks is still relatively intact—this is where much of the fuel oil aboard *Arizona* is stored (Fig. 16).

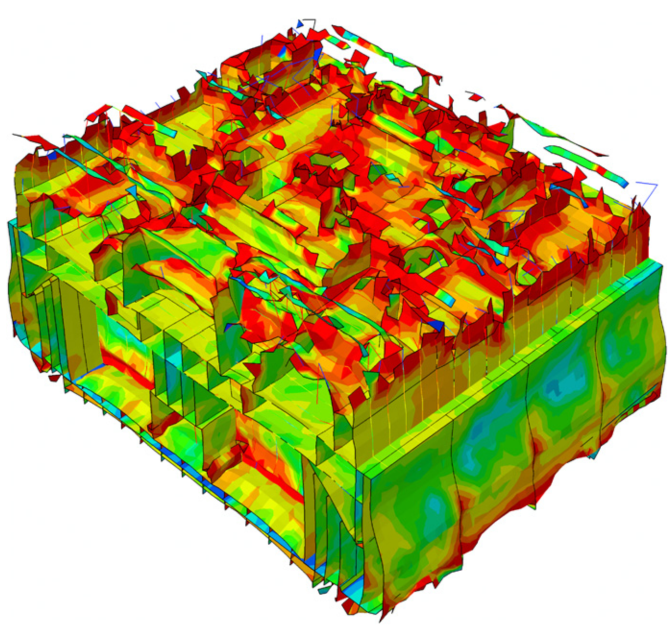

Fig. 16. Weight stresses after 90% thickness loss due to corrosion, approximate date = 2240 (NIST graphic).

5. Conclusions

Results of the USS *Arizona* FEA indicate that, after nearly seven decades on the bottom of Pearl Harbor, the wreck is approximately one-fifth to one-fourth of the way towards total loss of hull steel due to corrosion and subsequent collapse of key structural elements. A surprising aspect of the FEA results is that collapse is predicted to initiate in the side and bottom of the hull before any significant collapse events occur in the exposed regions of the upper decks. In addition, an important observation from this analysis is that, while the exposed decks above the harbor bottom will eventually become extensively deteriorated, the core cylinder of the wreck, consisting of the volume bounded by the third deck, the inner bottom and the side oil tanks, is still relatively intact even after 95% of steel thickness has corroded. This means that, according to projections from the FEA, many of the oil-containing spaces within the ship may retain integrity until the year 2250 or beyond. Based on our present information and understanding of the wreck and the processes affecting it, this may, in fact, be a conservative estimate.

We believe the hull section selected for analysis, frame 70–90, to be representative of the entirety of the aft half of the ship, although we purposefully designed the FEA to reflect a conservative, faster, corrosion rate than what is likely actually occurring on-site—in this case, we believe the FEA should present a worst case scenario rather than the most optimistic projection. The investigation and analysis of the hull section we modeled provides a conservative estimate of corrosion rates for two reasons. First, as discussed above, the hull section used in the model is adjacent to blast-damaged hull areas, and was therefore likely subjected to heat and blast damage during the explosion and sinking of the vessel. Because of this exposure, it is likely that these areas of the hull are subject to somewhat increased corrosion rates compared to areas further aft. The degradation of hull steel predicted by the FEA is therefore probably more accelerated in the modeled section of hull and actually slower in the rest of the hull further aft. Second, and more important, because hull corrosion is mostly an oxygen-driven process, the corrosion rates we measured on the hull's exterior (which has been subjected to normally oxygenated sea water) are likely much higher than corrosion rates in the vessel's interior spaces (which we know to be almost completely anaerobic). By using the higher corrosion rates measured from the hull's exterior for the entire model when designing the FEA, we produced a worst case scenario because interior corrosion rates are actually likely much lower.

In the future, the FEM can be increased in accuracy as better data are collected and key variables are added and refined. To date, however, the model closely matches observations by researchers on site. During site mapping and other research activities in the 1980s, NPS personnel noted little upper deck damage in the area of *Arizona*'s galley beyond that attributable to initial damage from the Pearl Harbor attack and subsequent salvage activities. No oil release from upper deck breaches was observed. These observations mesh well with the predictions from the model at 10% loss of steel from corrosion (which the model projects would happen by the year 1980). No upper deck collapsing is predicted by the model at the 10% degradation level, and none was observed during research from 1982 to 1986.

As the vessel reaches 20% corrosion thickness loss (projected to occur by the year 2020), the model predicts that upper deck areas

begin to show sagging of the beams and deck plates as they continue to thin. This corresponds well with recent (2006) observations of limited upper deck collapse in the modeled area, and increased release of secondary oil in the area as more breaches begin to open. To date, therefore, the FEM seems to be predicting actual behavior reasonably well. We, of course, cannot project the model's accuracy into the future without verification through long-term monitoring, and continued monitoring into the future is one of the recommended management actions to validate FEM accuracy as we move into the future.

The interdisciplinary research characterizing USS *Arizona*'s site formation processes using an FEA was designed to produce cumulative data whose synthesis will inform management actions regarding long-term stewardship of this historic battleship. Beyond informing management decisions about *Arizona*, we believe this research approach has produced results that contribute to the ongoing study of submerged iron and steel shipwreck site formation processes, and that are directly applicable to the numerous submerged iron and steel vessels worldwide. Because some aspects of the study remain ongoing and new data is being collected through long-term monitoring activities, conclusions will be refined and may change as data-gaps are filled and new information is added. Data presented here, however, represent the most comprehensive view of the ship based on observations, investigations, and experimentation to date. We have learned a great deal that will allow NPS and U.S. Navy managers to make informed decisions about immediate preservation needs within a stewardship framework.

Corrosion rates are highest on portions of *Arizona* in the shallowest water and lowest in the anaerobic environment below the current harbor bottom. Incorporating specific data into the FEM has indicated that the hull is deteriorating slowly: since sinking in 1941, the battleship has only progressed one-fifth to one-quarter to the way towards total loss of steel due to seawater corrosion. The model predicts that oil-containing spaces on *Arizona*'s lower decks will likely remain intact for centuries. As predicted, *Arizona*'s upper deck areas, closest to the water surface and with the highest corrosion rates observed on site, are experiencing increased deterioration at present. It is important to remember, however, that these areas are not integral to *Arizona*'s structural integrity, and do not include primary oil-containing spaces. All oil-containing spaces are deep below the present harbor bottom, within the structural core of the ship that is presently experiencing the lowest corrosion rates on site, and which are predicted to have not yet suffered significant corrosion.

In summary, USS *Arizona*'s complete structural deterioration, and eventual release of oil within its hull, is by all indications not imminent. This study has allowed us to quantify, and therefore better understand, the complex site formation processes taking place on *Arizona*'s hull. Based on the FEA, our management recommendation is that at this time there is no scientific justification to alter current management policies of *in situ* preservation coupled with systematic, long-term monitoring. There are critical variables that need to be refined for inclusion into a revised and expanded FEM, and continued research and monitoring on *Arizona* should be continued and any diversions from predicted results investigated. For the present, we recommend that status quo be maintained regarding any intervention in *Arizona*'s hull.

Acknowledgements

This research partnership is an example of public and private institutions working together effectively for public benefit, and it serves as a model for combining resources to cost-efficiently address issues important to both the American people and the international community. The project was funded with the support of the U.S. Department of Defense, Legacy Resources Management Program; Arizona Memorial Museum Association; USS *Arizona* Memorial; and NPS Submerged Resources Center. It would not have been possible to conduct the research without support and active contributions by many military units, academic institutions and researchers, commercial companies, non-profit organizations, and other federal agencies which are unfortunately too numerous to list here. We would like to thank the three anonymous reviewers for their insightful comments. Any errors in fact or reasoning, however, remain the sole responsibility of the authors.

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